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14. ABSTRACT

To develop an eigenmode or proper orthogonal decomposition (POD) modal representation of unsteady aerodynamic forces on oscillating flexible airfoils and wings and thereby reduce the size and cost of mathematical models for such forces by several orders of magnitude. Building on earlier work for two-dimensional inviscid flows, we seek to extend our models to three-dimensional flows with viscous effects included. Also a novel form of the harmonic balance (HB) method had been developed for determining limit cycle oscillations (LCO) of aeroelastic systems.

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FINAL TECHNICAL REPORT TO THE
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
"LIMIT CYCLE OSCILLATIONS (LCO) AND NONLINEAR AEROELASTIC WING RESPONSE: REDUCED ORDER AERODYNAMICS"

AFOSR GRANT NUMBER F49620-01-1-0139

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December 31, 2003

OBJECTIVE

To develop an eigenmode or proper orthogonal decomposition (POD) modal representation of unsteady aerodynamic forces on oscillating flexible airfoils and wings and thereby reduce the size and cost of mathematical models for such forces by several orders of magnitude. Building on earlier work for two-dimensional inviscid flows, we seek to extend our models to three-dimensional flows with viscous effects included. Also a novel form of the harmonic balance (HB) method had been developed for determining limit cycle oscillations (LCO) of aeroelastic systems.

RELATIONSHIP AND IMPORTANCE TO AFOSR

Success in this research will allow practical use in design of state-of-the-art CFD models (when recast in reduced order form) for aeroelastic analysis including the effects of active control and nonlinearities. With this capability, more accurate and timely investigations of flutter, limit cycle oscillations (LCO) and other aeroelastic phenomena will be possible, thereby substantially enhancing aerospacecraft performance and safety.

BASIC RESEARCH ISSUES

At the start of the work under this grant, some investigators questioned whether aerodynamic modes exist and, if so, could they be used to construct reduced order aerodynamic models.

It is now clear that aerodynamic modes provide a powerful and highly computationally efficient approach to constructing reduced order aerodynamic models. Eigenmodes are the basis for any modal analysis of a complex dynamical system, but the next basic research question was are there attractive alternatives to eigenmodes? It has been shown that proper orthogonal decomposition is a much more attractive way to determine an aerodynamic modal

representation. POD modes are easier to compute than eigenmodes for high dimensional CFD models and indeed POD modes may be used to compute aerodynamic eigenmodes (or balanced modes) if desired. Another important set of issues relates to the extension of this approach to three-dimensional, viscous flows with shock waves, including both static and dynamic nonlinearities. Current work is directed toward addressing these issues.

APPROACH AND STATUS OF EFFORT

Eigenmode and POD representations have been successfully constructed for isolated airfoils and for airfoils in cascade using potential flow models, the Euler fluid equations of motion and, for viscous flows, a potential flow plus boundary layer model. Our most recent results are for transonic flows with shock waves including viscous boundary layer effects. Initial results were for small, dynamically linear motions about a nonlinear steady flow. During the present reporting period large amplitude, nonlinear dynamic flows have been considered including the effects of viscosity.

This latest work has led to nonlinear dynamic models of transonic, viscous two-dimensional flows using a novel form of the harmonic balance method. To use such nonlinear dynamic fluid or aerodynamic models for determining LCO of aeroelastic systems, a highly computationally efficient dynamical model is needed to first determine the onset of flutter and LCO based upon either eigenmodes or modes determined from Proper Orthogonal Decomposition (POD) [1-9]. The latter are also sometimes called KL modes using the initials of the two inventors of these modes.

For wings in three-dimensional flow fields, incompressible potential equations were initially used to construct reduced order models. Subsequent work has extended this achievement to compressible potential and inviscid Euler equations of fluid motion. Our most recent work has produced results for viscous Navier-Stokes flows.

All reduced order modeling studies completed to date suggest that 50 or fewer aerodynamic modes are required for aeroelastic analyses and often the number of modes needed is fewer than 10 for many parameter combinations. By contrast, the original computational fluid dynamic models studied to date have as many as 250,000 degrees of freedom, and in their original form are not practical for aeroelastic design methods. CFD models for three-dimensional flows about a complete aircraft may have on the order of several million degrees of freedom, but we still expect the POD approach to be workable for such systems.

In addition, an experimental study has been made of bodies typical of wing and tip stores to determine stall and separated flow effects on limit cycle oscillations (LCO) [10]. This work suggests these effects are important at sufficiently large angles of attack, i.e. typically greater than 10 degrees at low speeds. Of course, such effects may occur at smaller angles of attack in transonic flow conditions.

A presentation at an earlier AIAA conference on LCO in delta wings with structural nonlinearities where the use of reduced order aerodynamic models is an essential enabling

technology is now available in a journal article [11]. [12] describes early transonic flow studies and [13] is an invited overview paper on our reduced order modeling work. Finally two presentations [14, 15] on extending our inviscid, transonic flow models were made at the International Forum on Aeroelasticity and Structural Dynamics 1999, Williamsburg, Virginia and these have now been accepted for journal publication.

Results for transonic flutter and LCO of an airfoil control surface with freeplay [16], transonic LCO analysis of an airfoil in pitch due to large shock motion [17], and transonic flutter analysis of a wing in 3D flow [18] are described in three papers presented at the AIAA 2001 SDM Conference. Flutter and LCO resulting from aerodynamic nonlinearities are being systematically investigated in the transonic range for airfoils in two-dimensional flow including large amplitude and viscous effects and/or viscous separated flow and results have been reported in [19-21]. Special emphasis is being given to theoretical-experimental correlation. Fig. 1 shows the LCO characteristics of an airfoil in two-dimensional transonic flow due to an aerodynamic nonlinearity arising from either large amplitude, inviscid shock motion or viscous separated flow about a supercritical airfoil, NLR 7301. Note the significant differences between the computed inviscid and viscous results and also the one experimental point. Fig. 2 shows another comparison between theory and experiment which is more encouraging.

Results have also been obtained for three dimensional flows about the AGARD 445.6 wing. Note again that the effects of viscosity on flutter and LCO may be significant [22,23]. See Figure 3. The inclusion of viscous effects resolves a major portion of the previously observed differences between theory and experiment for the flutter boundary and also shows a substantial impact on LCO.

SIGNIFICANT RESULTS AND ACCOMPLISHMENTS

The successful construction of eigenmode aerodynamic models has led to reductions in computational times for aeroelastic analyses of up to three orders of magnitude, i.e., a reduction in computational cost by a factor of up to 1,000. This permits for the first time the use of state-of-the-art computational fluid dynamics (CFD) models in aeroelastic analyses for design purposes. Also, greater insight into critical physical phenomena has been obtained by the observation and study of the interaction between the fluid eigenmodes and the better known structural modes.

An exploratory aeroelastic study for a simple delta wing with plate-like structural nonlinearities suggests such wings may be flown safely up to the linear flutter velocity and beyond. This gives promise of providing a way for the designers to consider reduced flutter margins and thereby enhance performance and safety.

And a novel harmonic balance method has shown great advantages in substantially improving the efficiency of LCO calculations with aerodynamic nonlinearities. Flutter and LCO results correlate well with experiment for both a supercritical airfoil and a wing configuration.

ACKNOWLEDGMENT/DISCLAIMER

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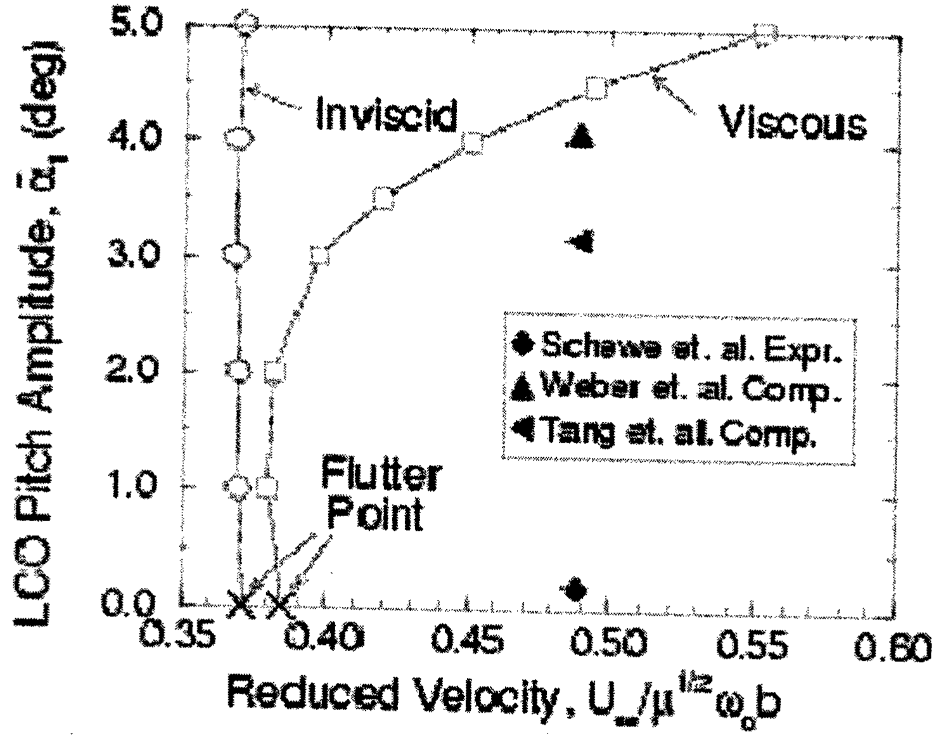

Shows the LCO characteristics of an NLR 7301 supercritical airfoil in two-dimensional transonic flow due to an aerodynamic nonlinearity arising from large amplitude, inviscid shock motion vs. separated viscous flow.

FIGURE 1

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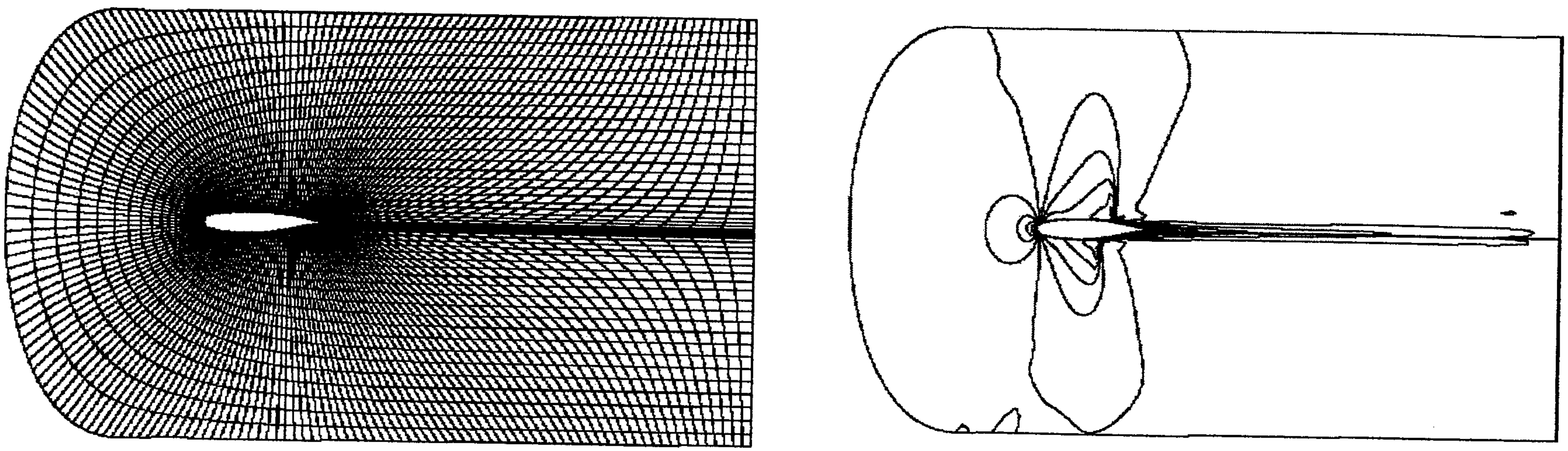

NLR 7301 Experimental Aeroelastic Configuration. Transonic LCO.
Correlation of Theory and Experiment. Effects of Wind Tunnel Wall Interference.

FIGURE 2a: Flow and Airfoil Geometry Plus Computational Grid

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NLR 7301 Airfoil in Wind-Tunnel Test Section
Calculated Single Degree-of-Freedom Flutter Trend

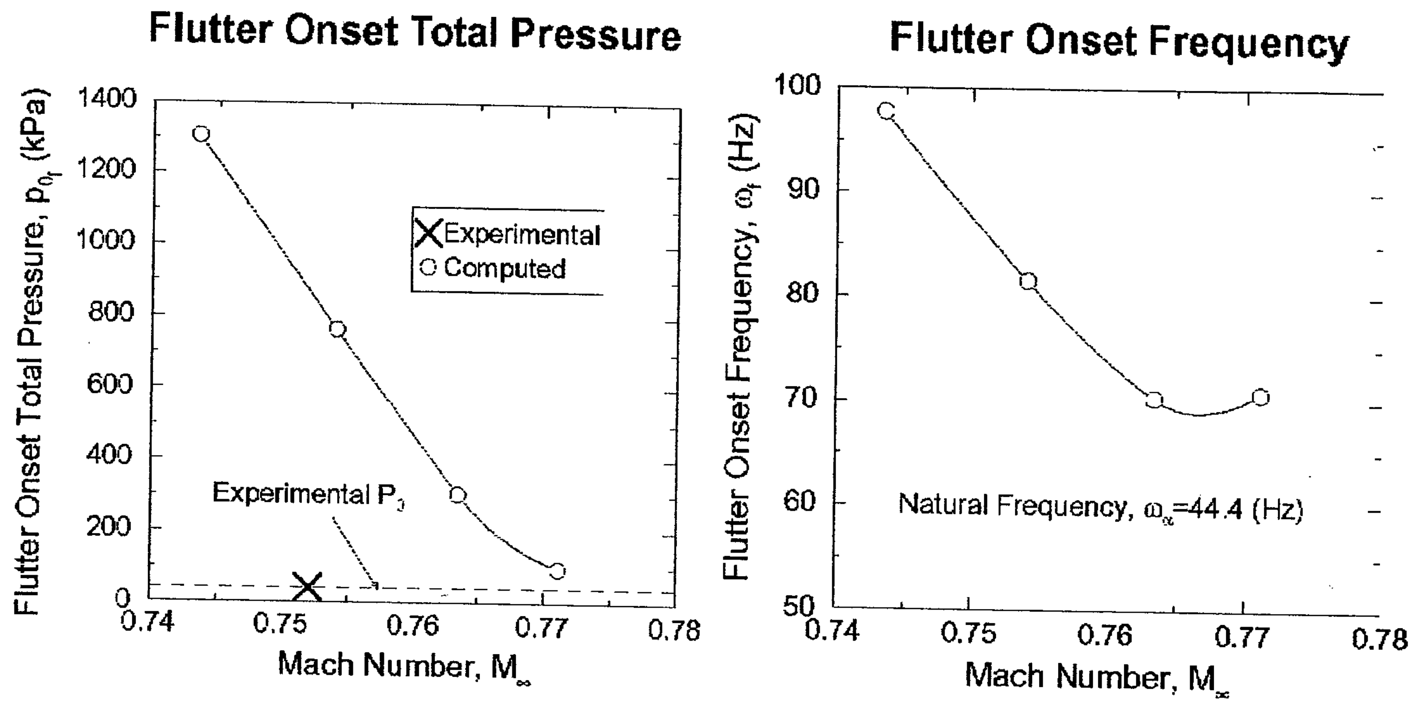
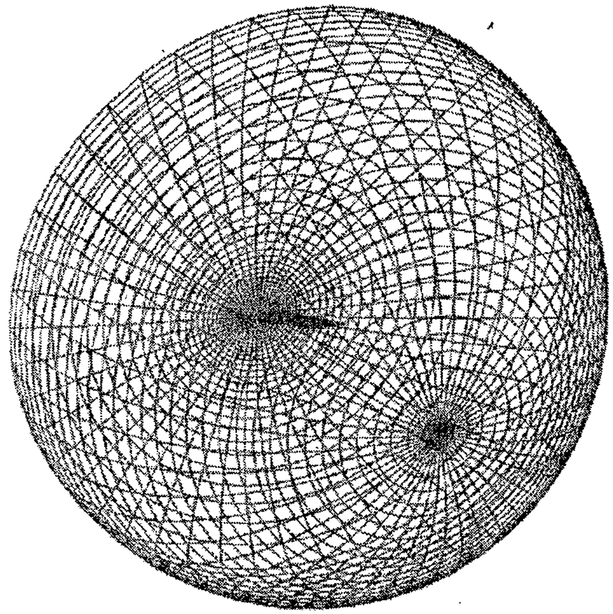
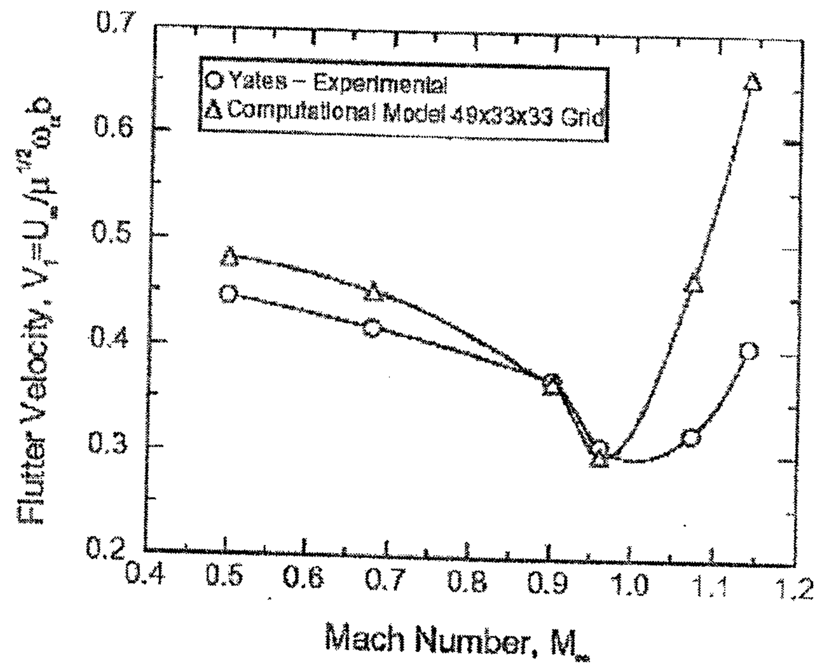


FIGURE 2b: Theoretical Flutter Boundary and Comparison with Experimental Data

Chart #3 (cont'd)

Accomplishments – New Scientific Findings
HB flutter solution of a 3D AGARD 445.6 wing





Correlates well with experimental measurements at M<1, but not M>1!

FIGURE 3a: Flutter Boundary for Reduced Flow Velocity vs. Mach Number

Chart #3 (cont'd)

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LCO Response Amplitude vs. Reduced Velocity

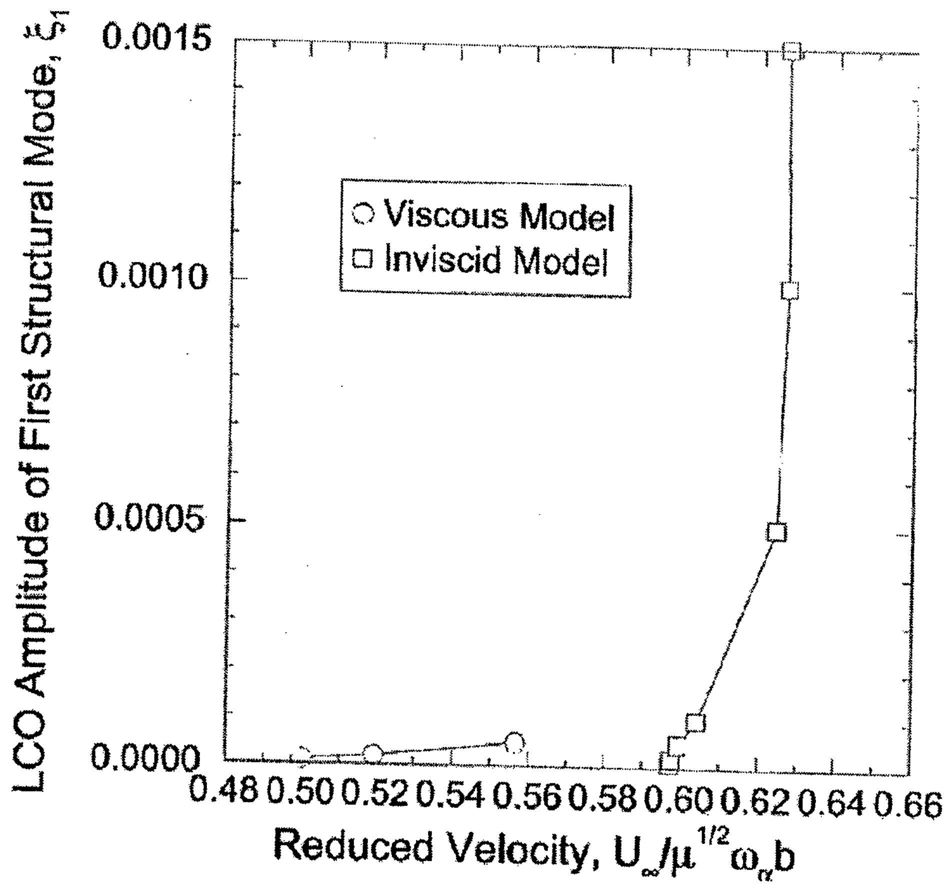

FIGURE 3b: LCO Amplitude vs. Reduced Flow Velocity For M = 1.141. Comparison of Inviscid vs. Viscous Calculations

Chart #3 (cont'd)

Limit Cycle Oscillations (LCO) and Nonlinear Aeroelastic Response: Reduced Order Models

AFOSR Grant Number F49620-01-1-0139

Earl H. Dowell
Kenneth C. Hall
Jeffrey P. Thomas
Duke University

September 2003

Relevancy

- Objective: To construct reduced order models (ROM) of unsteady aerodynamic forces to achieve orders of magnitude reduction in computational cost and model degrees of freedom

- A key enabling methodology to analyze and design for transonic flutter and limit cycle oscillations (LCO)

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Relevancy

- Five years ago, such work was pioneered at Duke. Now several research groups are pursuing such work. For example:

  Dr. Philip Beran, AFRL
  Dr. John Kim, Boeing

- A systematic approach has been taken, starting from two-dimensional models and adding the effects of compressibility, shock wave motion and now

  •Large shock motions
  •Viscosity

Relevancy

- Three dimensional flows have also been modeled for BOTH inviscid and viscous flows.

- Applications to aircraft systems (including UCAV), space launch vehicles (subsonic to hypersonic) and weapons such as aircraft stores.

Chart #1 (cont'd 2)

Background Information and Partnerships

- Traditional approaches are based upon classical theory that ignores shock waves and viscosity

or

- More elaborate CFD models that are very expensive computationally and thus not suitable for engineering analysis and design.

Background Information and Partnerships

- We are collaborating with industry and government (AFRL and NASA) through reports to the Aerospace Flutter and Dynamics Council and as a partner with ZONA Technology (funded by a STTR grant)

Innovation In Science

- First work to show how one can dramatically reduce the size, complexity and cost of physically sophisticated CFD models.
- New limit cycle oscillation (LCO) results for 2D and 3D flows with large shock motions and viscosity including correlations with experiment.

Figure 1: LCO of a Supercritical Airfoil: Effects of Large Shock Motion (Inviscid and Viscous Flow). Note the magnitude of the LCO as the flutter boundary is exceeded is quite different for inviscid vs. viscous flow.

Figure 2: Transonic LCO. Correlation of Theory and Experiment including the effects of wind tunnel wall interference. Figure 2a is the flow and airfoil geometry including computational grid. Figure 2b is a comparison of the theoretical flutter boundary with experimental data.

Figure 3: Flutter Boundary and LCO Amplitude for AGARD 445.6 Wing. Figure 3a is the flutter boundary and Figure 3b is the LCO Amplitude vs. Reduced Velocity for $M = 1.141$.

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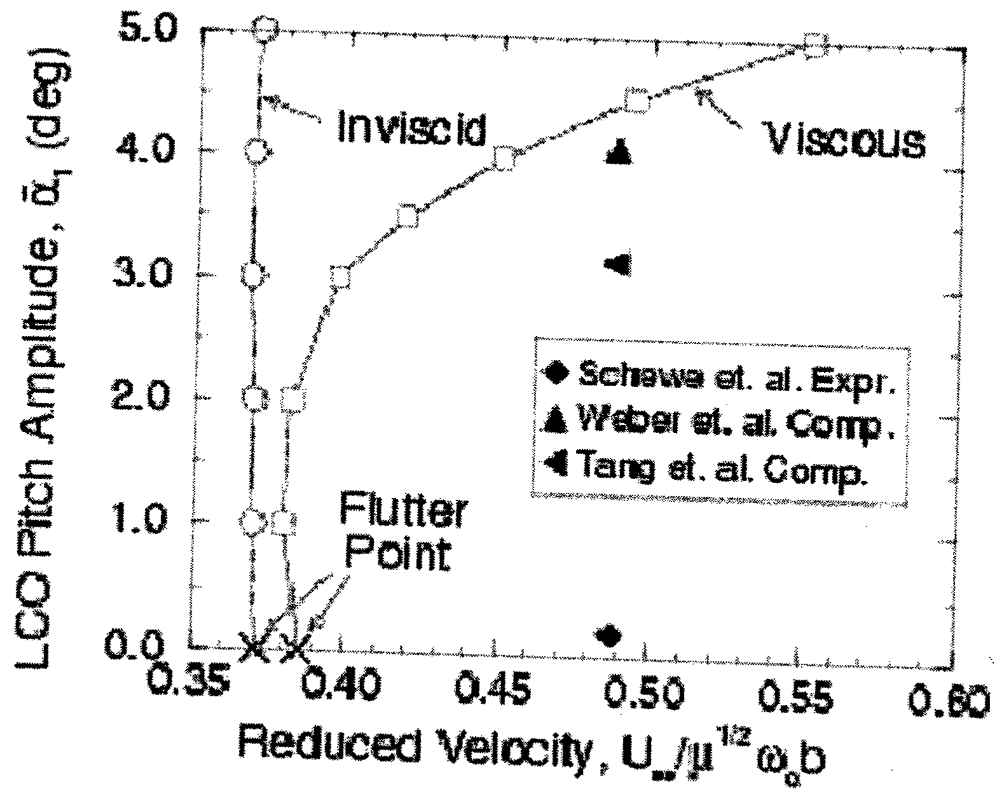
Innovation In Science

- Flutter calculations with a POD/ROM model are no more expensive and the model size is no larger for 3D flow than for 2D flow. However, constructing a 3D vs. a 2D POD/ROM is conceptually more complex and somewhat (factor of 2 to 3) more computationally costly.

- A novel Harmonic Balance (HB) method has been shown to be an effective approach for computing LCO due to aerodynamic nonlinearities arising from large shock motions and viscous separated flows.



Shows the LCO characteristics of an NLR 7301 supercritical airfoil in two-dimensional transonic flow due to an aerodynamic nonlinearity arising from large amplitude, inviscid shock motion vs. separated viscous flow.

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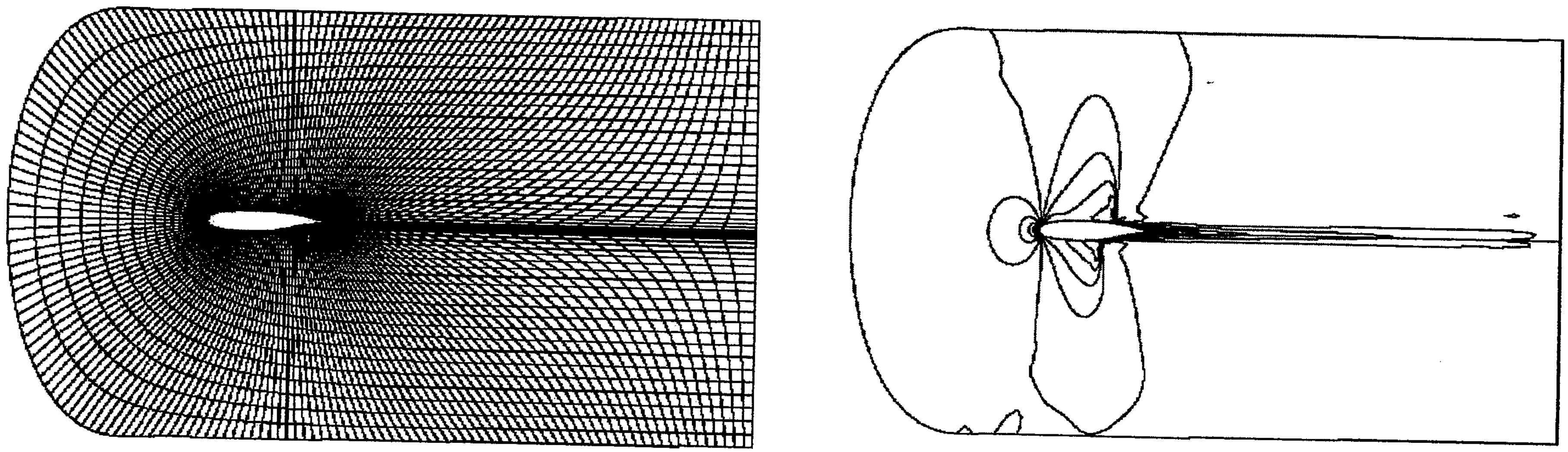

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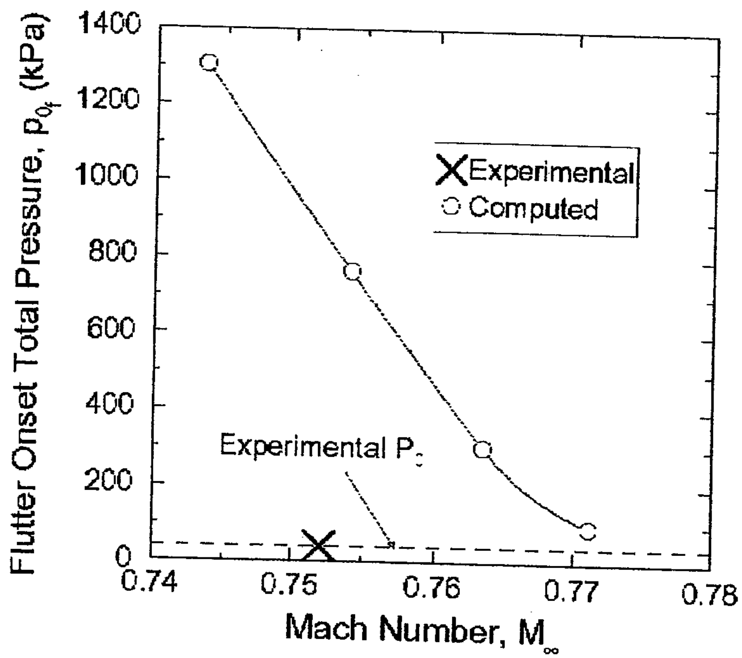
NLR 7301 Airfoil in Wind-Tunnel Test Section
Calculated Single Degree-of-Freedom Flutter Trend



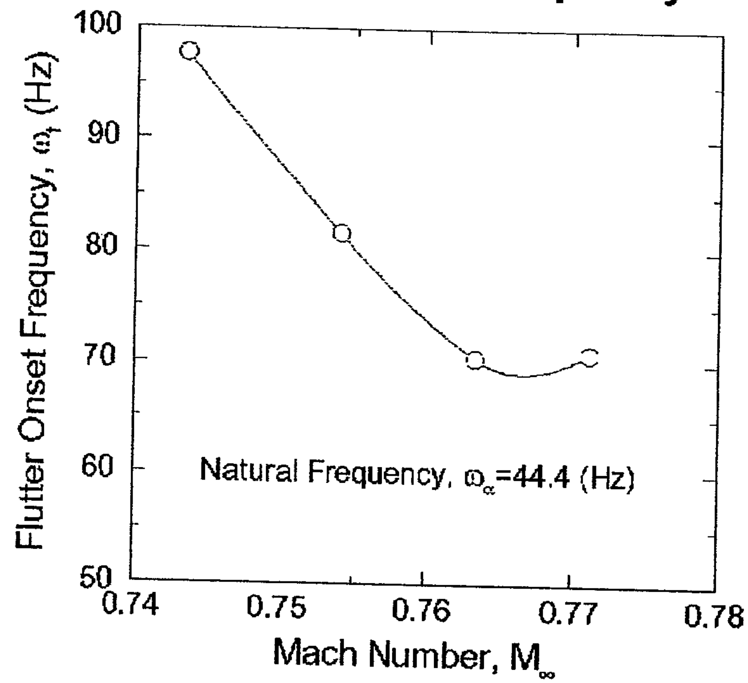
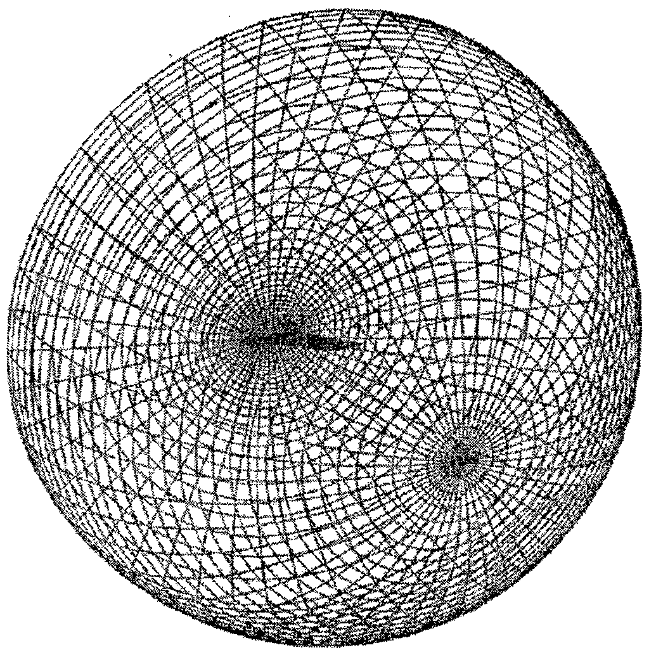


FIGURE 2b: Theoretical Flutter Boundary and Comparison with Experimental Data

Chart #3 (cont'd 4)

Accomplishments – New Scientific Findings
HB flutter solution of a 3D AGARD 445.6 wing



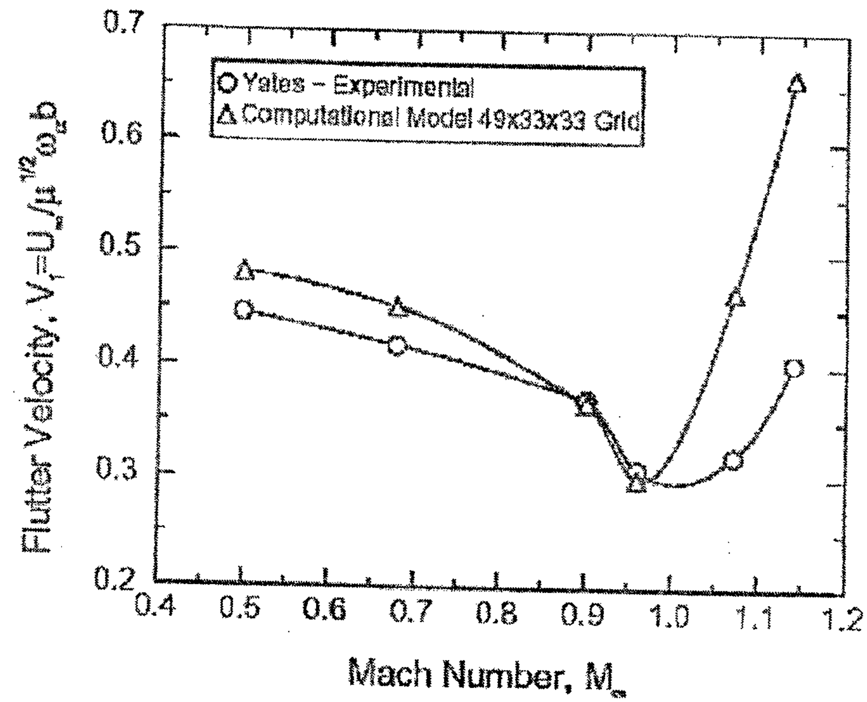


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FIGURE 3a: Flutter Boundary for Reduced Flow Velocity vs. Mach Number

Chart #3 (cont'd 5)

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LCO Response Amplitude vs. Reduced Velocity

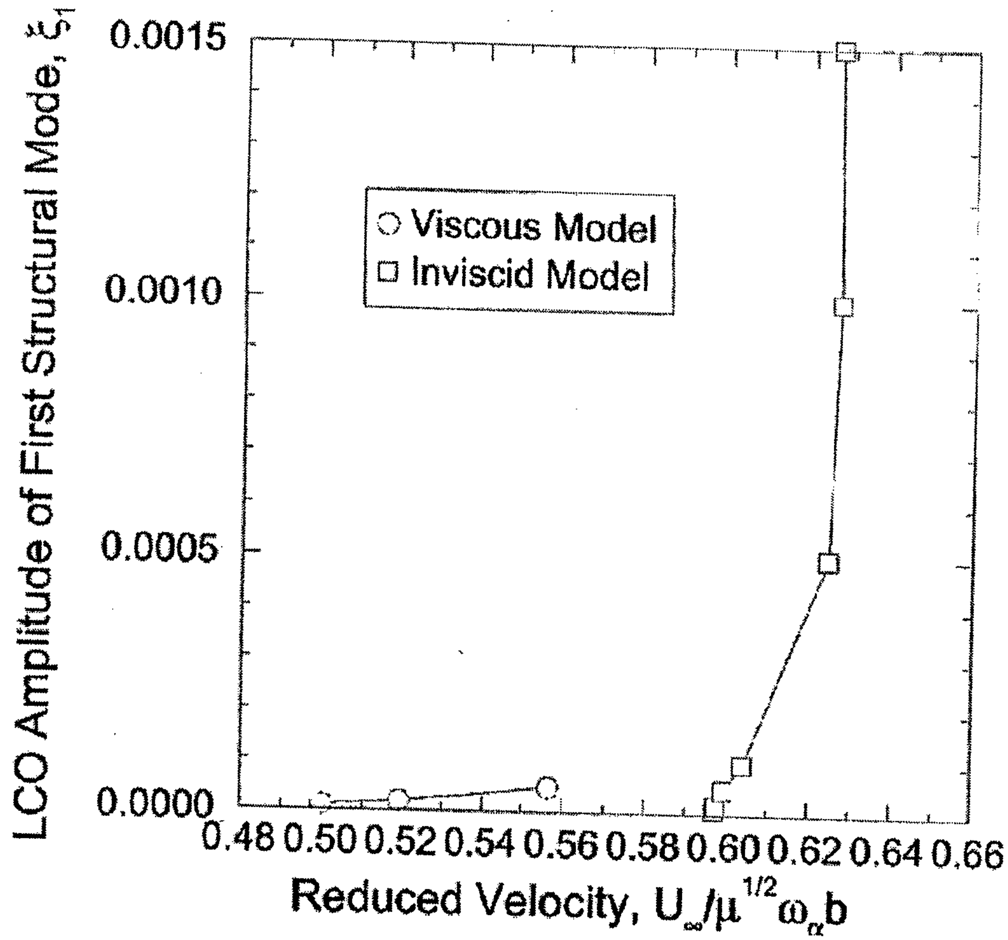

FIGURE 3b: LCO Amplitude vs. Reduced Flow Velocity For M = 1.141. Comparison of Inviscid vs. Viscous Calculations

Chart #3 (cont'd 6)

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Innovation In Design

- POD/ROM models in combination with an innovative HB method make transonic flutter and LCO analysis feasible for engineering research and design.

- POD/ROM and HB methods are expected to impact currently operational flight vehicles (F-16, F-18 and F-22) and also future aerospacecraft (JSF, UCAV, new launch vehicles).

- Flutter and LCO are important drivers to these new methods developments, but gust analysis response and design of smart structures will also substantially benefit.